Developing a novel custom cutting guide for curved periacetabular osteotomy

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Abstract

Purpose Curved periacetabular osteotomy (CPO) produces excellent clinical results, but the surgical procedure is technically demanding, and severe complications related to the osteotomy have been reported. To provide a safe, accurate surgical procedure, we have developed a novel method for setting the cutting line and direction. We have designed and made a custom cutting guide for individual patients. The purpose of the study was to evaluate the efficacy of this new method and cutting guide.

Methods The cutting line was designed on a full-scale three-dimensional plaster model made from computed tomography (CT) data for each case. The surface of each plaster model was colour-coded according to the distance from the centre of the femoral head. A custom cutting guide was designed based on this cutting line on the workstation. A titanium custom cutting guide was fabricated using rapid prototyping technology. The cutting guide instructed the cutting direction of the osteotome. We evaluated the outcomes for seven consecutive hips in seven patients who underwent CPO using the system between April and December 2011. All perioperative complications were recorded. The accuracy of the cutting line was evaluated using CT data obtained 2 weeks after the operation.

Results There were no major complications related to the osteotomy such as posterior column fracture or intra-articular osteotomy. The actual cutting line corresponded almost exactly to the planned cutting line in all cases.

Conclusions The colour-coded plaster model and the custom cutting guide were effective for avoiding severe complications associated with a CPO.

Keywords: Curved periacetabular osteotomy, acetabular dysplasia, custom cutting guide, rapid prototyping, computed tomography

Introduction

Acetabular dysplasia is a common cause of secondary hip arthrosis, and redirection of the acetabulum into a normal position is the most physiological solution for a young adult [1,2]. The dial or spherical osteotomy described by Wagner [3] and Eppright [4] and rotational acetabular osteotomy described by Ninomiya and Tagawa [5] provide satisfactory clinical results [6,7]. Although these surgical approaches and procedures have been modified [8,6,7], postoperative hip abductor weakness and vascular damage to the transferred acetabulum are potential complications of these methods [8,9].

The Bernese periacetabular osteotomy [10] provides good coverage of the femoral head and preserves hip abductor muscle strength and the vascular supply of the transferred acetabulum. Several authors have reported good clinical results using this method [11-14]. Naito et al. modified the osteotomy and reported on the use of a curved periacetabular osteotomy (CPO) [15,16]. The CPO requires a smaller skin incision, and the spherical cutting promotes the stability of the transferred acetabulum and requires a shorter rehabilitation period [16]. Although the Bernese periacetabular osteotomy and the CPO have several advantages, the procedure is technically demanding and has a significant learning curve [17,18,10]. Severe complications, including a posterior column fracture, intra-articular osteotomy, and sciatic nerve palsy, have been reported [16-18].

Recent developments in computer imaging technology allow for detailed surgical planning, and there are several methods for transferring surgical planning to the operation field. One such method is computer-assisted navigation, which is an effective tool for improving the accuracy of surgery [19,20]. However, this technique has several drawbacks such as the learning curve, errors related to a shift of the registration frame, obscuration of tracking optical array devices by surgeons or tools, expensive equipment, and time-consuming procedures. Another method for transferring the preoperative planning to the operation field is the use of image-based navigational templates. These are designed based on a preoperative computed tomographic (CT) image that fits into a unique position on the individual patient’s bone, and which is used to design a precise cutting line. This technique can be used to reproduce the planned position of the template by adjusting the position of the contact faces of the template until they fit exactly on the bone. Neither iterative time-consuming work under radiographic control or registration procedures nor any additional computerized equipment is needed intraoperatively.

Since 2008, we have performed CPO on patients with symptomatic acetabular dysplasia, and we have experience with some cases of severe complications including posterior column fracture and intra-articular osteotomy. To provide a safe and accurate surgical procedure, in 2011 we developed a computer-assisted surgical planning and image-based navigational template for performing the CPO. In this paper, we describe the effectiveness of these methods and review our short-term results.

Patients and methods

Patients and study design

Between April and December 2011, we evaluated seven consecutive hips in seven patients who underwent a CPO using the titanium custom cutting guide and who were followed for at least 6 months. All seven patients were female and had experienced hip pain for at least 3 months. They had radiographic evidence of acetabular dysplasia (Crowe grade 1 [21]) and minimal or no radiographic evidence of osteoarthritis (Tönnis Grade 0–1 [22]). Patients were allowed out of bed on the second postoperative day, and partial weight bearing was allowed (approximately one-third of body weight) 2 weeks after the surgery. Full weight bearing was allowed 6 weeks after the surgery. A CT scan was performed 2 weeks after the surgery. Any incorrect cutting such as intra-articular osteotomy or posterior column fracture was recorded. Postoperative CT data were superimposed on the preoperative CT data, and the accuracy of the cutting line was evaluated. The actual cutting radius in each patient was calculated at three different points on the cutting line (named Points 1, 2, and 3 in Fig. 1c) and was compared with the planned cutting radius. All perioperative complications were recorded. The protocol was approved by our institutional ethical review committee, and written informed consent was obtained from all patients after the potential risks, and the aim of the study, were fully explained. To examine whether the rate of serious osteotomy-related complications decreased with the use of the custom cutting guide, clinical data were also collected for 11 consecutive patients who underwent a CPO without the uses of the custom cutting guide between April 2008 and March 2011.

Planning of the cutting line and cutting direction

For the preoperative planning, a full-scale three-dimensional (3D) plaster model was made. A CT scan of the pelvis of each patient was performed before surgery. The images comprised the entire pelvis with a voxel size of 0.625 mm in all three axes. The CT data were transferred to commercially available image-processing software, VGStudio MAX2.0 (Volume Graphics GmbH, Heidelberg, Germany), which was used to reconstruct a 3D model of the bony structures, and bone tissue voxels were extracted. First, we identified the rotational centre of the acetabulum. Because deformity of the femoral head was minimal in all cases, we decided that the rotation centre would correspond to the centre of the femoral head. The centre of the femoral head was decided manually in the sagittal and coronal planes of the CT data. Next, all voxels representing bone tissue were classified into four groups according to their distance from the centre of the femoral head (0 mm to 40 mm, 41 mm to 50 mm, 51 mm to 60 mm, and ≥61 mm). These grouped voxels were colour-coded (Fig. 1a). These data were used to generate the full-scale 3D model, and the bony model was made using a plaster-based full-colour 3D printer (ZPrinter 450; Z Corporation, Burlington, MA) (Fig. 1b, c). The ideal cutting line is thought to be a sphere when centred on the femoral head; however, the actual cutting line has some restrictions. First, the cutting line should start at the supra-acetabular portion just above the anterior inferior iliac spine, where the origin of the quadriceps femoris muscle attaches to the bone (Fig. 2a). Second, to avoid a posterior column fracture, the distance between the inner edge of the posterior column and the cutting line should be no less than 15 mm (Fig. 2a). The cutting line was determined manually on the plaster model following these criteria (Fig. 2a).

Design and fabrication of the custom cutting guide

After the cutting line was decided, the 3D model data were transferred to another commercialized software, FreeForm® Modeling™ version 10 (SensAble Technologies, Woburn, MA), and a custom cutting guide was designed using this software (Fig. 2b). The cutting guide has three or four holes to fix to the pelvis with a φ1.5 mm Kirschner wire. The guide has also a short fin whose surface is parallel to the cutting surface (Fig. 2b). With this fin, the direction of the osteotome can be prescribed to avoid an intra-articular osteotomy. Stereolithography format files for the custom guide were prepared for rapid prototype fabrication of physical models, and the titanium custom guides were fabricated using a selective laser melting machine (EOSINT M270; Electro Optical Systems GmbH, Munich, Germany) using commercially available pure titanium powder. The adaptation, stability, and indicated cutting direction of the cutting guide were evaluated on the plaster model (Fig. 2c, d). The custom-made titanium guide, designed with adequate adaptation and stability and with proper cutting direction, was sterilized in an autoclave and used during the operation. The data were recorded and analysed for each patient.

Surgical procedure

The surgical procedure has been described in detail previously [16]. Briefly, an anterior skin incision about 12 cm in length was made along the iliac crest to a position distal to the anterior superior iliac spine (ASIS). The ASIS is osteotomized with the inguinal ligament and sartorius muscle attached. The lateral femoral cutaneous nerve was retracted medially. The supra-acetabular portion and the quadrilateral space were exposed, and the custom cutting guide was fixed to the pelvis with 1.5 mm Kirschner wire. The fit was confirmed using an image intensifier (Fig. 3a, b). The osteotomy started just above the anterior inferior iliac spine using a C-shaped osteotome. After the osteotomy of the supra-acetabular region was completed, the osteotomy of the quadrilateral space was performed. After the final osteotomy of the superior ramus of the pubis and ischium was completed, the acetabular fragment was rotated laterally and fixed in the ideal position with two or three poly-L-lactic acid screws. Autologous blood donation of 800 g was performed before the surgery, and Cell Saver System (Haemonetics Japan, Tokyo, Japan) was used in the surgery in all patients.

Statistical analysis

Fisher’s exact test was used to compare the rates of osteotomy-related complications between the seven patients whose operation used the custom cutting guide and the 11 patients whose operation did not use the guide. We used R (R for 2.14.1 GUI 1.43) for the analysis.

Results

Planning of the cutting line and cutting direction

The planned cutting line was not spherical in all cases. The average distance between the supra-acetabular portion just above the anterior inferior iliac spine and the rotation centre was 55 mm (range from 50 mm to 60 mm), and the average distance between greater sciatic notch and the rotational centre was 56 mm (range from 53 mm to 58 mm). To avoid a posterior column fracture, the cutting radius at the sciatic notch should be 41 mm (56 mm minus 15 mm) on average. Therefore, the cutting radius becomes slightly smaller as the cutting line nears the obturator foramen (Fig. 2a).

Efficacy of the custom cutting guide

The custom cutting guide fit well in all seven patients, as confirmed using the image intensifier during surgery (Fig. 3a, b). No major complications, including a posterior column fracture or intra-articular osteotomy, were recognized in any patient. Postoperative dysaesthesia of the anterior femoral region occurred in two patients. Temporary incomplete sciatic palsy occurred in one patient, but was restored completely within 3 days. Blood transfusion was not needed by any patient. In the 11 patients whose operation did not use the custom cutting guide, three osteotomy-related complications occurred. These included one case of posterior column fracture and two cases of intra-articular osteotomy. The rate of osteotomy-related complications did not differ significantly between the two groups ($p > 0.1$).

The actual cutting line corresponded almost exactly to the planned cutting line in all patients, as confirmed by the postoperative 3D-CT (Fig. 4a, b). The difference between the actual cutting radius and the planned cutting radius was measured at three different points in each patient (Fig. 1c). The difference was less than 5 mm in all measurements, although the difference was larger at Point 3 (Fig. 5).

All patients but one resumed preoperative levels of activity by 4 months after surgery. One patient complained of inguinal pain, which might have resulted from irritation of the psoas muscle by the cut edge of the pubis.

Discussion

Periacetabular osteotomy with reorientation of the acetabulum is a well-established treatment for developmental dysplasia of the hip. The CPO offers many advantages, including preservation of abductor muscle strength [23] and blood supply to the rotated acetabulum, and a short skin incision. In addition, the osteotomy is spherical and can avoid anterior overcorrection and non-union of the rotated acetabulum [16]. However, the CPO has a steep learning curve, especially for performing an osteotomy of the quadrilateral surface [16]. It is also difficult to confirm the cutting line and direction through the small incision. To establish the safety of the surgical method used in the CPO, previous studies have reported on the appropriate cutting line and the insertion angle of the C-shaped osteotome [15,24]. However, performing the osteotomy accurately remains difficult because of the limited direct view of the quadrilateral surface and anatomical indices. Individual differences in the size and the shape of the pelvis are other factors that affect the accuracy of an osteotomy [17].

To allow for accurate preoperative planning of the cutting line, we developed a full-scale colour-coded plaster model, which provides a view of the approximate cutting line at a glance and allows the surgeon to confirm that the cutting line is parallel to the concentric coloured circles (Fig. 2a). Further, the custom cutting guide made in titanium helped us complete the difficult osteotomy in a safe and accurate manner. Ideally, the cutting line is spherical; however, the actual cutting line was not completely spherical in all seven cases because of the restrictions mentioned above. The transferred acetabulum was stable enough to fix two or three poly-L-lactic acid screws in all cases, and we did not identify any gaps requiring a bone graft in any patient.

Accurate set up of the guide in the proper position is critical to our method. The guide has two arms, which can catch the greater sciatic notch and the supra-acetabular portion just above the anterior inferior iliac spine (Fig. 2c, d). These two arms can stabilize the guide and help set the guide in the proper position. We confirmed the position using an image intensifier to make sure (Fig. 3a, b). The cutting guide has a small fin whose surface is identical to the cutting sphere surface (Fig. 2b–d); therefore, the direction of the C-shaped osteotome can be prescribed. Our cutting guide is a relatively simple and easy-to-use solution that facilitates precise preoperative planning and appropriate intraoperative implementation. The conventional intraoperative procedure is preserved, and no additional intraoperative registration steps, computerized equipment, space, or personnel are needed. Continual fluoroscopic monitoring can be avoided, fewer radiographs are needed, and the duration of the intervention is reduced. In our seven patients, neither posterior column fracture nor intra-articular osteotomy was detected. In the 11 consecutive patients whose operation did not use the custom cutting guide, three cases of osteotomy-related complications were noted. These data show the efficacy of the custom cutting guide, although the difference in the complication rate between groups was not significant. The postoperative CT data showed that the actual cutting line corresponded almost exactly to the initial planned cutting line in all cases, which confirms the effectiveness of the custom cutting guide. Furthermore, the difference between the actual cutting radius and the planned cutting radius was less than 5 mm in all measurements. The reason for the larger difference at Point 3 might be related to the subtle movement of the guide at this point. Because the arm of the guide at the supra-acetabular region can be seen directly, the arm of the guide is fixed firmly and the guide can rotate slightly around this fulcrum. Point 3 is at the opposite end of the guide, and there may be more movement at this point than at the other two points.

It is our impression that the rotation procedure of the acetabular fragment was smoother than the method that we used previously. The limitation of our system is that it takes several days to design and make the colour-coded plaster model and the custom guide. In addition, the operation of the software is relatively complicated, and some training is needed to become proficient.

There are several limitations to this study. First is the lack of an appropriate control group. We compared the clinical results with those of 11 consecutive eleven patients who underwent a CPO before we began using the custom cutting guide. As mentioned above, CPO has a steep learning curve, and it may not be appropriate to compare the clinical results of two types of the surgery, which were performed during different periods. The small number of cases is another limitation. Further study using the custom guide will strengthen our good clinical results.

The CPO has several advantages for the treatment of hip dysplasia. However, the surgical procedure is difficult, and an inappropriate osteotomy can cause serious complications including posterior column fracture or intra-articular osteotomy. The full-scale colour-coded plaster model and the titanium custom cutting guide were effective tools for avoiding severe complications related to the osteotomy in the CPO.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figure legends

Fig. 1 The reconstructed 3D-CT surface of the pelvis was colour-coded (a) according to the distance from the centre of the femoral head (rotational centre). The figure shows an actual colour-coded plaster model seen from the top (b) and from inside (c). (c) The black dotted line shows the cutting line and the white dotted line shows the iliopectineal line. To evaluate the accuracy of the osteotomy, the cutting radius was measured using CT data at the three different points indicated by the three arrowheads. Point 1 shows the initial cutting point at the supra-acetabular region; Point 2 shows the intersection point between the cutting line and iliopectineal line; Point 3 shows the the cutting line at the level of the ischial spine

Fig. 2 (a) The cutting line was planned and drawn manually on the plaster model (dotted line). The black arrow shows the initial cutting point just above the anterior inferior iliac spine. The white arrow shows the width of the posterior column, which should be no less than 15 mm. (b) The custom cutting guide was designed on the workstation based on the chosen cutting line. The arrowheads indicate the short fin used to determine the direction of the osteotome. The C-shaped osteotome is also shown in the figure. (c) and (d) The adaptation and stability of the titanium cutting guide were confirmed on the plaster models

Fig. 3 (a) The custom cutting guide was fixed with three Kirschner wires and the fitting to the pelvis was confirmed using an image intensifier. (b) The cutting line can be confirmed with an oblique view of the pelvis

Fig. 4 (a) The figure shows the planned cutting line and the designed custom cutting guide (without fin) on the preoperative 3D-CT view. (b) The planned cutting line and the cutting guide were superimposed on the postoperative 3D-CT view. The actual cutting line corresponded almost exactly to the planned cutting line

Fig. 5 The figure shows the difference between the planned cutting radius and the actual cutting radius at three different points; Point 1, 2, and 3. The difference was less than 3 mm at Point 1 and Point 2 in all seven patients. The difference was larger at Point 3

Fig. 1

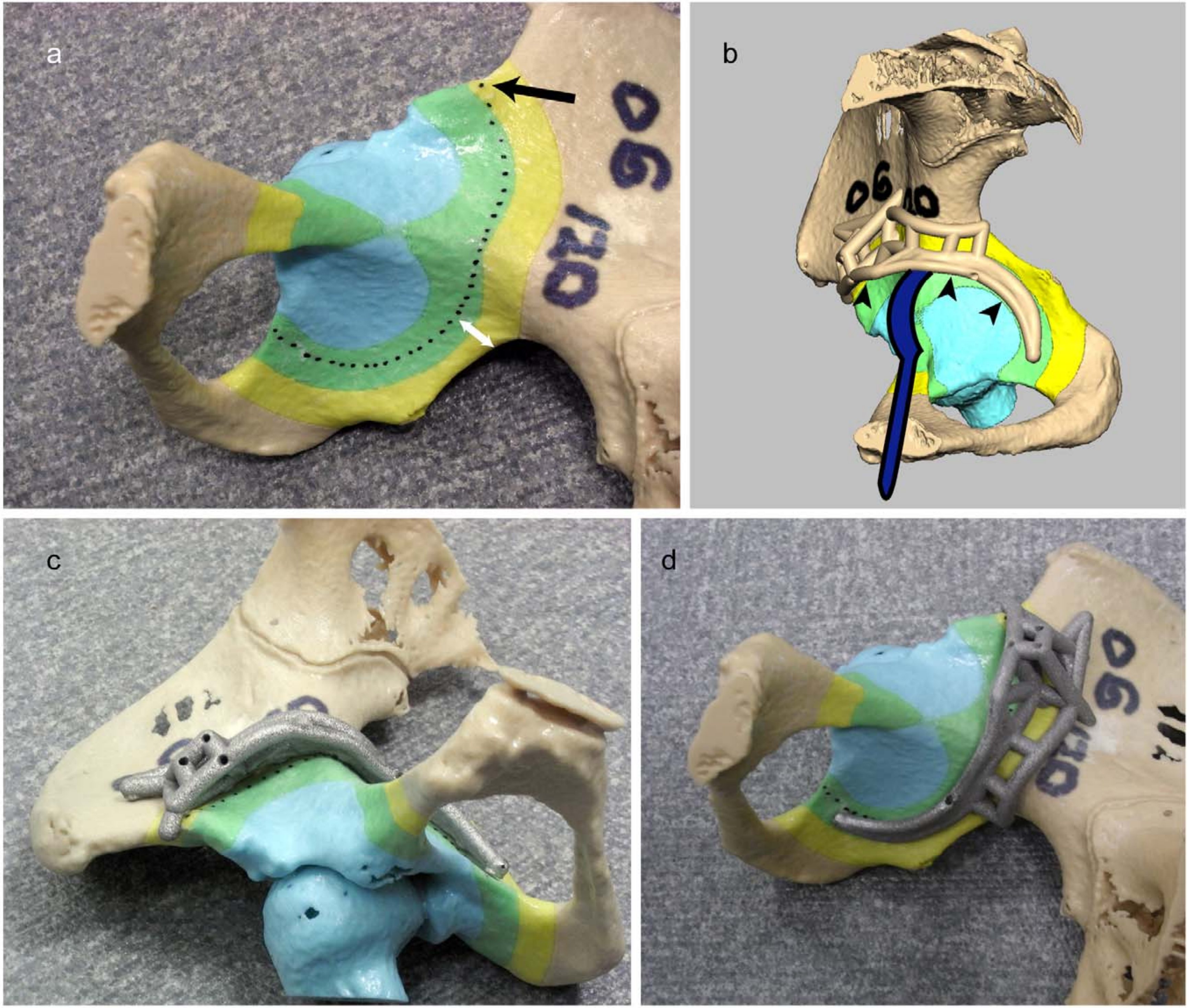

Fig. 2

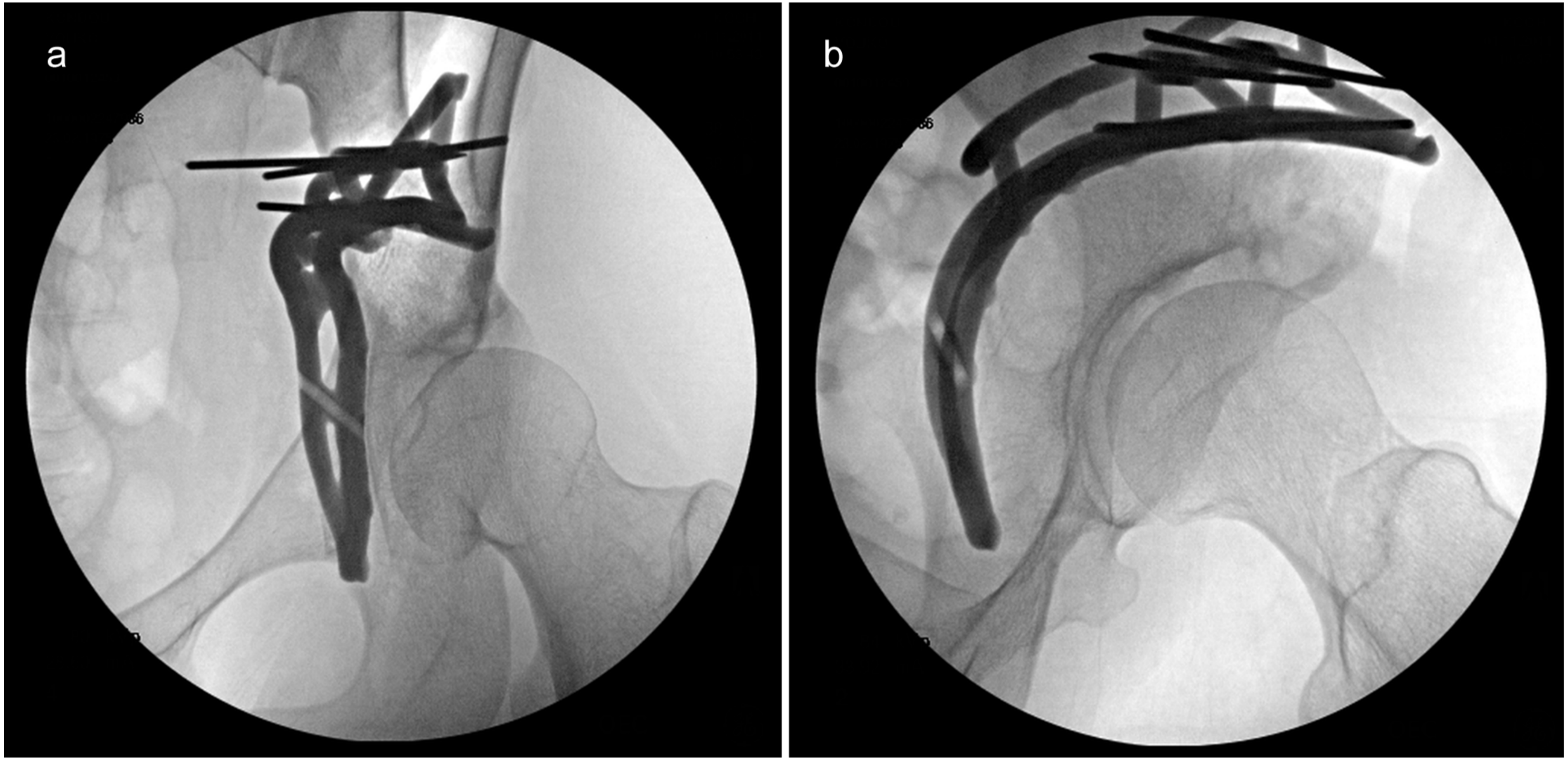

Fig. 3

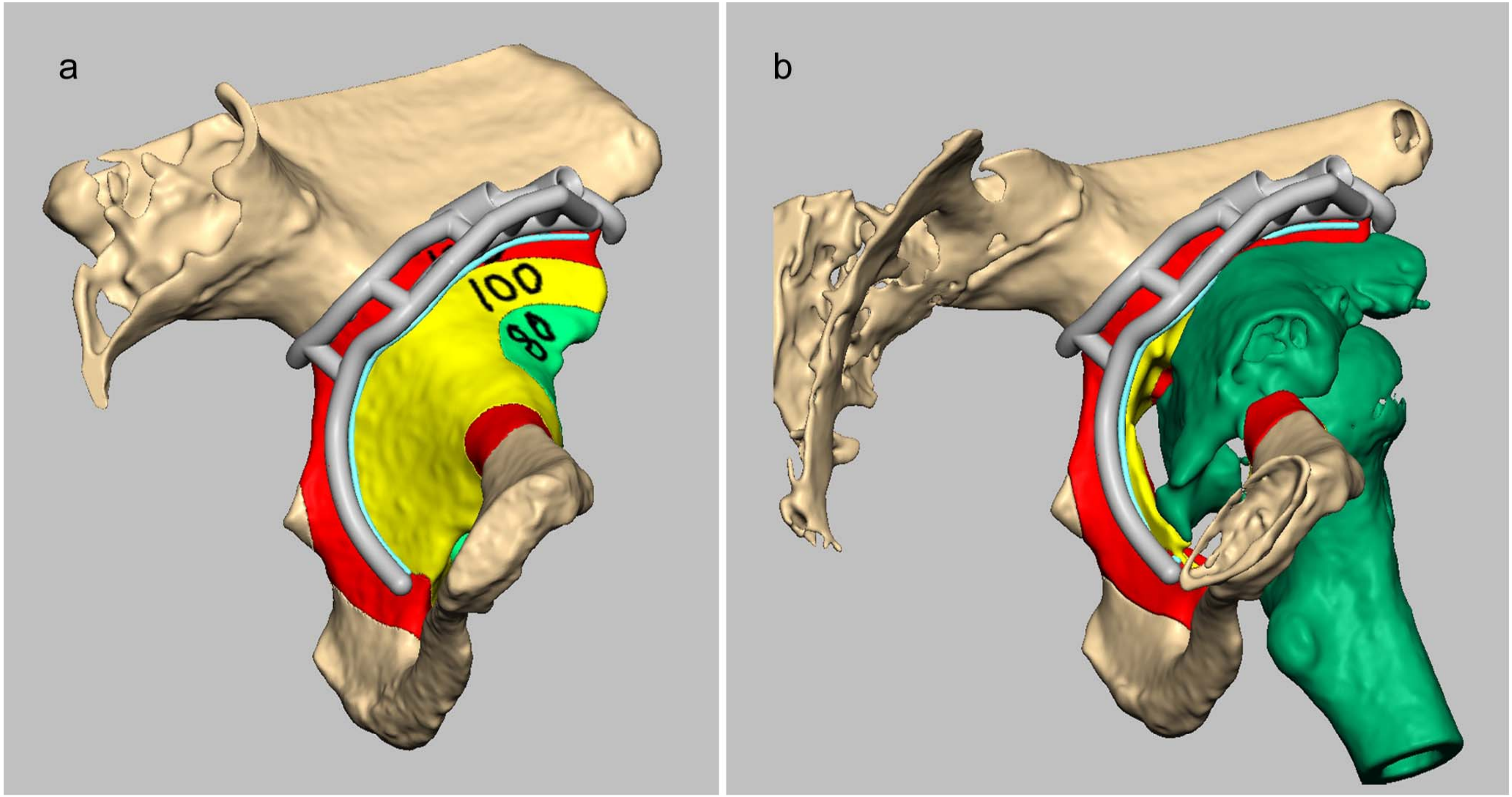

Fig. 4

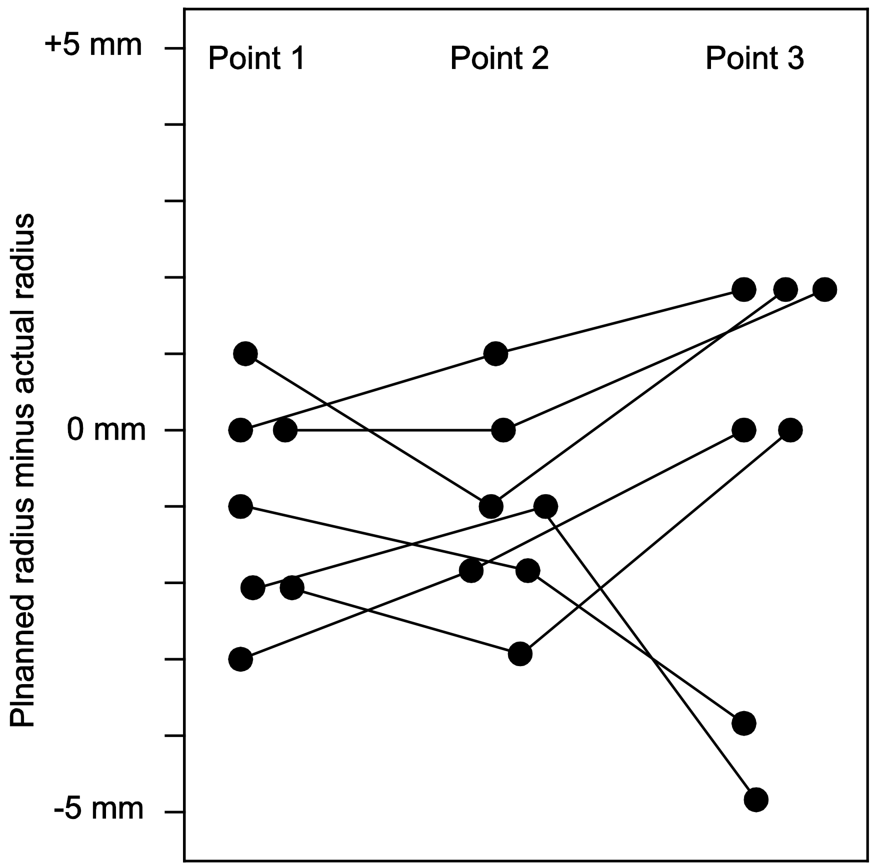
+5 mm
0 mm
-5 mm
Plnanned radius minus actual radius
Point 1
Point 2
Point 3

Fig. 5